IM/DD vs. 4-PAM Using a 1550-nm VCSEL over Short-Range SMF/MMF Links for Optical Interconnects

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Abstract: We experimentally compare the performance of 10.9-Gb/s IM/DD and 5-GBd 4-PAM modulation formats over 5-km SMF and 1-km MMF links, employing a commercially-available 1550-nm VCSEL as an enabling technology for use in optical interconnects.

OCIS codes: (200.4650) Optical interconnects; (200.6715) Switching ; (140.7260) Vertical cavity surface emitting lasers

1. Introduction

In the near future, high-performance computing (HPC) optical interconnects, will likely use parallel point-to-point binary intensity modulation (IM)/direct-detection (DD) optical links to achieve transmission rates up to 100 Gb/s [1]. For this purpose, directly-modulated, vertical-cavity surface-emitting laser (VCSEL) arrays in conjunction with multimode fibers (MMFs), as well as 1.55-μm DFB lasers in conjunction with single mode fibers (SMFs), might be used [2]. M-ary intensity modulation formats, such as quaternary-pulse amplitude modulation (4-PAM) can be used to provide high effective data rates with acceptable cost and complexity, compared to conventional IM/DD that has been used so far [3]. The power consumption of 4-PAM and several advanced modulation formats, for use in next-generation data applications was reviewed in [4], while the performance of 4-PAM using VCSELs has been demonstrated in [3], [5].

In this paper, first, we investigate the transmission performance of a commercially available 1550-nm single-mode VCSEL [6] employing 1.25-Gb/s and 10.9-Gb/s IM/DD, over 100-m/5-km SMF and 100-m/1-km 50.7-μm diameter OM-4 MMF point-to-point optical links. Error-free transmission is achieved in all implemented scenarios, while a ~1 dB receiver sensitivity penalty arises in the longest-reach MMF (1-km) and SMF (5-km) links. Next, we compare, by experiment the performance of non-return-to-zero (NRZ)-IM/DD to the alternative 4-PAM modulation format, generated by the same 1550-nm VCSEL [6]. 4-PAM transmission over SMF links up to 5 km and short (100 m) MMF links is achieved at bit error rate (BER)<10^{-3}. The adoption of M-ary intensity modulation in short-range WDM optical interconnects might be beneficial in the sense that it reduces the line rate by a factor of two and, therefore, the cost and the speed/consumption of electronics, at the expense of an increase in sensitivity and transceiver complexity (i.e., due to the DSP-based receiver). The single-mode 1550-nm VCSEL technology proves to be an enabling technology towards this direction.

2. Experimental setup

As a first set of experiments, 1.25-Gb/s and 10.9-Gb/s IM/DD links are investigated. The experimental setup for the IM/DD configuration is shown in Fig. 1. The VCSEL is mounted on an evaluation board and is biased by a current source. The signal used to directly modulate the 1550-nm VCSEL is produced by a pulse pattern generator (PPG) operating at 1.25 or 10.9 Gb/s and is fed into the VCSEL via a bias-T. The driving voltages are set to V_{p-p}=0.934 V and V_{p-p}=0.840 V for the 1.25 Gb/s and the 10.9 Gb/s experiments, respectively. The bias currents are set to 18.46 mA and 18.51 mA and the extinction ratio is 6.97 dB and 5.67 dB for the 1.25 Gb/s and the 10.9 Gb/s case, respectively. The driving voltages and the bias currents are adjusted to the aforementioned values, by using the eye diagram on the sampling oscilloscope, in order to achieve the optimum extinction ratio and minimize the pulse overshoots. Then, the modulated signal is launched over 100 m of SMF or MMF, 1 km MMF, and 5 km SMF spools. At the receiver's side, a variable optical attenuator is used to adjust the received optical power (P_{RX}), which is subsequently monitored via a 20 dB-coupler. Finally, the signal is detected using a 10-GHz bandwidth single-mode (or multi-mode) photodetector. Then, the signal is electrically amplified and BER measurements as a function of P_{RX} are performed. The back-to-back case, in the absence of any fiber between the Tx and the Rx, is also investigated. We note here that the value of the current and the driving voltages are slightly optimized for each transmission scenario.

As a second experiment, the performance of 10-Gb/s 4-PAM point-to-point links is investigated. The experimental setup used for this study is shown in Fig. 2. The 4-PAM signal is generated using two pseudo-random binary sequences (PRBSs) provided by a PPG operating at 5 Gb/s, in order to achieve approximately the same capacity as in the 10.9-G/s IM/DD case. One of the electrical signals is delayed with respect to the other by one

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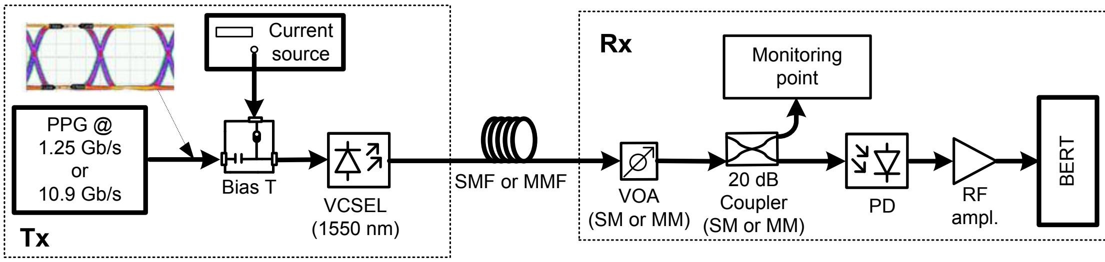


Fig.1 Experimental configuration for the 1.25-Gb/s or 10.9-Gb/s point-to-point links using IM/DD.

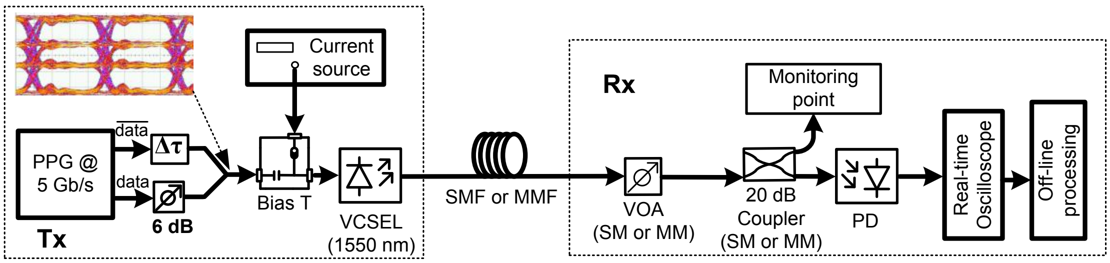


Fig. 2 Experimental configuration for the 10 Gb/s point-to-point links using 4-PAM.

symbol period using a microwave delay-line (denoted by Δτ in Fig. 2), so that the two PRBSs can be decorrelated. The second waveform is attenuated by 6 dB in order to obtain half the peak-to-peak voltage value with the respect to the other branch. The two signals are then combined through a 3-dB coupler. Next, the 4-PAM signal is fed to a bias-T and is used to directly modulate the 1550-nm VCSEL, which is DC-biased by a current source through the second input of the bias-T. The driving voltages at the PPG are $V_{p\text{-}p}$=1.223 V and the VCSEL's bias current is set to I_{bias}= 20.38 mA. The signal is transmitted over 100 m and 5 km of SMF, and over 100 m and 1 km of MMF, and is finally detected using a photodiode. The received optical power (P_{RX}) is swept before detection and BER measurements are carried out by sampling and storing the photocurrent on a digital sampling oscilloscope (DSO). The samples are then processed off-line using *Matlab*.

3. Results and discussion

The results for the IM/DD experimental study are presented in Fig. 3, for the back-to-back case (circles), and after transmission over 100-m SMF (triangles), 5-km SMF (squares), 100-m MMF (diamonds), and 1-km MMF (stars). Solid and dashed lines represent the 1.25-Gb/s and 10.9-Gb/s IM/DD data rates, respectively. Representative eye diagrams for error-free operation, for the back-to-back case and after transmission over 1 km MMF and 5 km SMF are shown in Table 1. Focusing on the solid curves, almost the same sensitivity requirements exist for SMF links up to 100 m and MMF links up to 1 km when employing 1.25 Gb/s. There is negligible penalty between the back-to-back curve, and the 100-m SMF, 100-m MMF and 1-km MMF curves at BER=10^{-9}. Extending the transmission up to 5 km of SMF leads to 1 dB penalty in sensitivity. In the case of 10.9-Gb/s IM/DD, there is ~0.5 dB penalty for transmission over 100-m SMF and 100-m MMF, and >1 dB penalty for transmission over 1-km MMF, compared to back-to-back. Transmission of 10.9-Gb/s IM/DD over less than 5-km of SMF fiber leads to 1.5-dB power penalty at BER=10^{-9}. This penalty is due to intersymbol interference (ISI), as indicated by the corresponding eye diagram in Table 1.

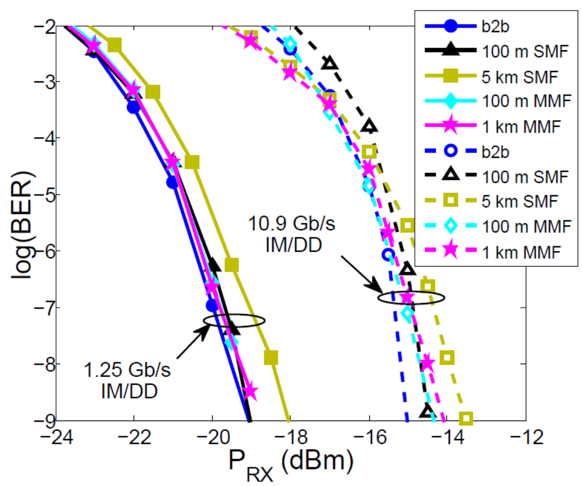


Fig. 3 BER vs P_{RX} for 1.25-Gb/s (solid lines) and 10.9-Gb/s IM/DD (dashed lines) using the 1550-nm VCSEL over 100-m/5-km SMF and 100-m/1-km MMF.

The experimental results for transmission of 10-Gb/s 4-PAM over SMF and MMF links are shown in Fig. 4 and Fig. 5, respectively (filled markers). For comparison, results for 10.9-Gb/s IM/DD (open markers), already presented in Fig. 3, are also shown in the same plots. More specifically, Fig. 4 shows measurements for the back-to-back case (squares), after transmission over 100-m SMF (circles) and over 5-km SMF (triangles). We observe that 10-Gb/s 4-

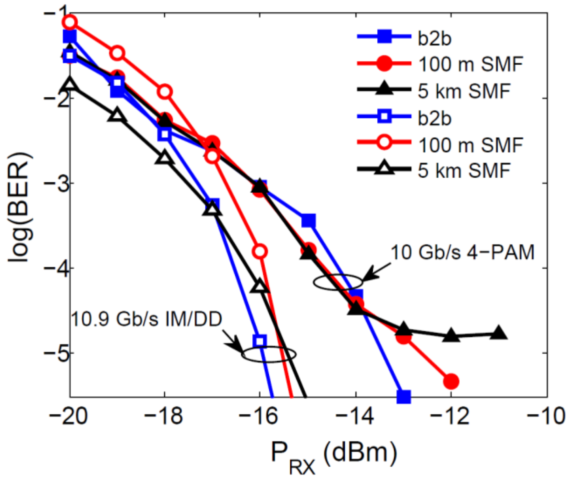


Fig. 4 BER vs P_{RX} for 10-Gb/s 4-PAM (filled markers) and 10.9-Gb/s IM/DD (open markers), in SMF links.

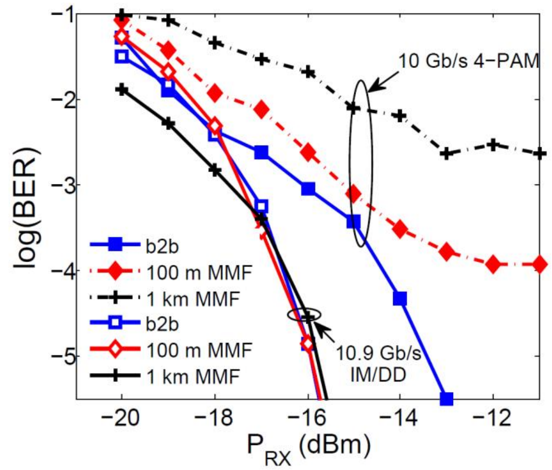


Fig. 5 BER vs P_{RX} for 10-Gb/s 4-PAM (filled markers) and 10.9-Gb/s IM/DD (open markers) in MMF links.

PAM could be transmitted over 5 km of SMF fiber links with no penalty at BER=10^{-3}. Nevertheless, error floors arise at lower BERs, which sets a limit on the performance of the link. The effect is more pronounced for longer distances, i.e., up to 5 km of SMF. Results in Fig. 4 reveal that substituting IM/DD by 4-PAM in 100 m/5 km SMF links for the same capacity, leads to approximately 2-dB penalty in P_{RX} at BER=10^{-4}. Reach is limited for 4-PAM up to less than 5 km SMF, since low BER values are not attainable (for longer distances).

In Fig. 5, focusing in the results depicted with filled markers, we observe that 10-Gb/s 4-PAM performs much worse in MMF than in SMF links (shown in Fig. 4), as expected. More precisely, there is a 2-dB penalty in sensitivity at BER=10^{-4} compared to back-to-back, for transmission over 100 m of MMF. Performance is severely degraded after transmission over 1-km MMF links, making the achievement of such transmission impossible. Error floors arise also in Fig. 5, as in Fig. 4 for SMF links, but this time for higher BER values. The performance of 4-PAM is 1.5-dB worse than the one of IM/DD measured back-to-back and 2.5-dB worse for 100-m MMF links at BER=10^{-4}. Error free transmission over 1-km MMF for 10-Gb/s 4-PAM cannot be achieved. The received eye diagrams for error free transmission for 1.25-Gb/s and 10.9-Gb/s IM/DD are shown in Table 1 in rows (a) and (b), respectively. 4-PAM eye diagrams are also shown in row (c) for back-to-back and after transmission over 5-km SMF for BER≈10^{-4}, as well as for the lowest BER value shown in Fig. 5 for 100-m MMF.

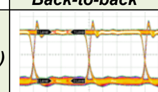
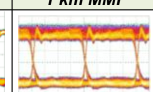
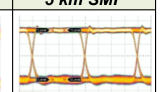
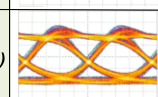
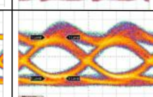
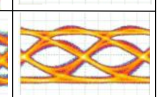
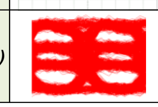
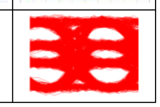
	Back-to-back	*1 km MMF*	*5 km SMF*
(a)			
(b)			
(c)			

Table 1: Received eye diagrams back-to-back, and after transmission over 1-km MMF and 5-km SMF. (a) 1.25-Gb/s IM/DD; (b) 10.9-Gb/s IM/DD, at BER≈10^{-9}; and (c) 10-Gb/s 4-PAM at BER≈10^{-4}.

4. Conclusion

We experimentally investigated the performance of a commercially-available 1550-nm VCSEL for point-to-point rack-to-rack optical interconnects using both IM/DD and 4-PAM, in various transmission scenarios in terms of length and type of fiber. Error free transmission is achieved for IM/DD, both in low and high data rates for reach up to 1 km MMF and 5 km SMF without a significant sensitivity penalty. For the 4-PAM, the FEC limit is achieved for transmission over 5-km SMF/100-m MMF links. These results indicate that 1550-nm VCSELs, in conjunction with multilevel amplitude modulation, are an enabling technology for next-generation WDM short-reach optical interconnects.

5. References

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